



Cellulosic feedstock production on Conservation Reserve Program land: potential yields and environmental effects

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Abstract

Producing biofuel feedstocks on current agricultural land raises questions of a ‘food-vs.-fuel’ trade-off. The use of current or former Conservation Reserve Program (CRP) land offers an alternative; yet the volumes of ethanol that could be produced and the potential environmental impacts of such a policy are unclear. Here, we applied the Environmental Policy Integrated Climate model to a US Department of Agriculture database of over 200 000 CRP polygons in Iowa, USA, as a case study. We simulated yields and environmental impacts of growing three cellulosic biofuel feedstocks on CRP land: (i) an Alamo-variety switchgrass (*Panicum virgatum* L.); (ii) a generalized mixture of C4 and C3 grasses; (iii) and no-till corn (*Zea mays* L.) with residue removal. We simulated yields, soil erosion, and soil carbon (C) and nitrogen (N) stocks and fluxes. We found that although no-till corn with residue removal produced approximately 2.6–4.4 times more ethanol per area compared to switchgrass and the grass mixture, it also led to 3.9–4.5 times more erosion, 4.4–5.2 times more cumulative N loss, and a 10% reduction in total soil carbon as opposed to a 6–11% increase. Switchgrass resulted in the best environmental outcomes even when expressed on a per liter ethanol basis. Our results suggest planting no-till corn with residue removal should only be done on low slope soils to minimize environmental concerns. Overall, this analysis provides additional information to policy makers on the potential outcome and effects of producing biofuel feedstocks on current or former conservation lands.

Keywords: biofuel, biomass, carbon, Conservation Reserve Program, erosion, nitrogen, no-till corn, residue removal, switchgrass

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Introduction

In December 2007, the US Congress enacted the Energy Independence and Security Act (EISA), mandating an increase in annual renewable fuel volumes from ca. 34 billion L in 2008 to 136 billion L by 2022 (U.S. Congress, 2007). Of this 136 billion L total, ca. 60 billion L are required to come from cellulosic feedstocks. Despite this mandated increase, it is uncertain where these cellulosic feedstocks will be cultivated. Agro-economic modeling suggests that cellulosic feedstocks could replace current commodity crops and pastureland (U.S. DOE, 2011), potentially exacerbating the ‘fuel vs. food’ dilemma (Tilman *et al.*, 2009).

US Conservation Reserve Program (CRP) land could offer an alternative land-use type for cultivation of these

feedstocks. Established by the 1985 Farm Bill and administered by the US Department of Agriculture (USDA) Farm Service Agency (FSA), the CRP is the largest agricultural land-retirement program in the US (Stubbs, 2013). The program offers annual payments to agricultural landowners in exchange for the establishment of perennial cover, providing environmental benefits, including increased carbon (C) sequestration, wildlife habitat, and reductions in soil erosion and nutrient runoff (Allen & Vandever, 2012). Despite these benefits, the amount of CRP land has steadily declined since reaching a peak enrollment of 14.9 million ha in 2007. In the 2008 Farm Bill, the US Congress capped the program at 12.9 million ha (U.S. Congress, 2008) and again reduced the enrollment cap to 9.7 million ha in 2014 (U.S. Congress, 2014). Growing cellulosic feedstocks on CRP land might offer a means to both produce ethanol and maintain CRP land under perennial cover. This raises, however, important questions

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regarding whether environmental benefits could be maintained under cellulosic feedstocks.

Here, using a modeling approach, we explored two timely questions: (i) how productive is CRP land for cellulosic feedstock cultivation? And (ii) what are the environmental effects of this production? To answer these questions, we employed the Environmental Policy Integrated Climate (EPIC) model in a spatially explicit framework and USDA-FSA field-level CRP polygons for Iowa, USA. We simulated the cultivation of three potential biofuel feedstocks on CRP land: (i) Alamo-variety switchgrass (*Panicum virgatum* L.); (ii) a generalized mixture of C4 and C3 grasses; (iii) and no-till corn (*Zea mays* L.) with residue removal. We simulated yields, soil erosion, and soil C and nitrogen (N) stocks and fluxes, with comparisons made to an unharvested grass cover.

Materials and methods

We used EPIC, a comprehensive biophysical and biogeochemical process-based model, to simulate the production capacity and environmental effects of using CRP land located in the state of Iowa. The EPIC model has been extensively tested for many agricultural cropping systems, and applied to understand agronomic and environmental impacts of alternative management practices and climate change (Wang *et al.*, 2012). The crop growth and soil organic carbon modules of EPIC have been examined against field observations from numerous sites across the world (Wang *et al.*, 2005; He *et al.*, 2006; Izaurrealde *et al.*, 2006, 2007; Causarano *et al.*, 2007, 2008; Apezteguía *et al.*, 2009; Schwalm *et al.*, 2010; Zhang *et al.*, 2013), including on marginal and CRP land (Izaurrealde *et al.*, 2006; Gelfand *et al.*, 2013). This has made it a useful tool for assessing conservation effects of the CRP (FAPRI, 2007; USDA-FSA, 2008, 2010). Key components of EPIC include plant growth and productivity, C and nutrient cycling, soil erosion, and greenhouse-gas emissions. More information about the methods used in the EPIC simulations is provided in Data S1.

We applied a spatially explicit integrative modeling framework for EPIC, developed by Zhang *et al.* (2010, 2015), whereby we combined multiple data layers to define modeling units. We were granted provisional access to a 2008 USDA-FSA database of farm-level CRP polygons for Iowa, and in adherence to stipulations, all results shown in this paper are rescaled-up to the county or state-level. Maps of CRP parcels for Iowa, soils [from the Soil Survey Geographic (SSURGO) database], and county boundaries were discretized to raster format with a grid resolution of 30 m, and were further combined to define over 200 000 homogeneous spatial modeling units with a total area of ca. 290 000 ha. For each modeling unit, we further derived elevation and climate information from the Shuttle Radar Topography Mission digital elevation model (Farr *et al.*, 2007) and re-analysis North-American Land Data Assimilation System 2 (NLDAS-2; ldas.gsfc.nasa.gov/nldas/), respectively. More information about the spatial data used is provided in Data S2. We employed the Python-based parallel computing software by Zhang *et al.* (2013) to execute EPIC in parallel on

the Department of Energy Evergreen cluster, and compiled spatially explicit modeling results into relational databases linked to GIS maps for geospatial analysis and presentation.

Using this framework, we modeled the effects of using CRP land for cellulosic feedstock production. We restricted our simulations to the potential conversion of CRP under grass cover, specifically three conservation practices (CP): CP1 (introduced grasses), CP2 (native grasses), and CP10 (established grasses) covering ca. 80, 58, and 152 thousand ha, respectively, according to the USDA-FSA database (Fig. 1). To initialize the soil C and N pools prior to the simulated treatments, we ran the model for 30 years with the generic C3/C4 grass mixture as land-cover and using the NLDAS-2 data from 1979 through 2008. We then simulated three treatments harvested annually: (i) switchgrass; (ii) the generalized C4/C3 grass mixture; and (iii) no-till corn with residue removal (hereafter, these feedstocks are referred to as 'switchgrass', 'grass mixture', and 'no-till corn', respectively). Although, the no-till corn yielded both cellulosic and grain ethanol, we were primarily interested in cellulosic ethanol feedstocks, and therefore chose to simulate continuous corn with residue removal and did not simulate it with a soybean rotation.

We simulated each treatment for 30 years, again using the 1979 through 2008 NLDAS-2 data. For the establishment of these three treatments, land-use conversion from the C3/C4

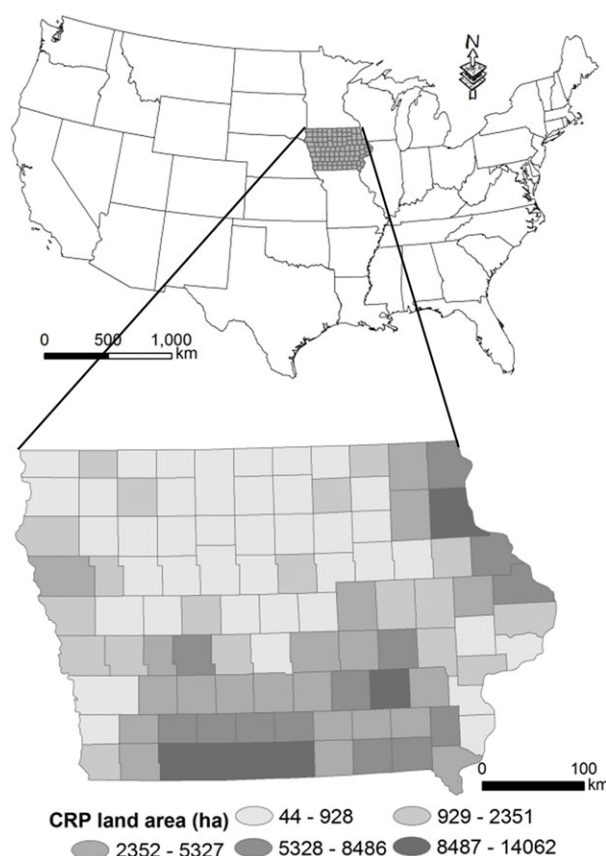


Fig. 1 Map of simulated Conservation Reserve Program (CRP) area by county in Iowa, USA.

baseline was simulated without tillage as suggested by Gelfand *et al.* (2011). The fertilization levels for perennials were chosen to be consistent with previous studies (Schmer *et al.*, 2008; Gelfand *et al.*, 2013), with switchgrass having a N application rate of 60 kg N ha⁻¹ yr⁻¹ while C3/C4 grasses receiving a one-time application of 40 kg N ha⁻¹ in the first establishment year. The no-till corn received 140 kg N ha⁻¹ yr⁻¹, slightly less than the average N application rate for corn between 2001 and 2010 in Iowa (ca. 147 kg N ha⁻¹ yr⁻¹; USDA-ERS, 2015). We simulated a moderate corn stover removal rate of 50% (Karlen *et al.*, 2014). All results were compared to the generic C3/C4 mixture without harvesting, which was re-established at year zero, but received no fertilizer amendment.

Outputs modeled included: aboveground biomass and grain yield, erosion, and soil C and N stocks and fluxes. The latter included CO₂ emissions as well as N runoff and leaching. To gain insights into variation in simulated yields and environmental impacts, we tested for correlations with slope and land-capability class. Land-capability classes (1 through 8) are assigned by the USDA-Natural Resources Conservation Service to indicate the suitability of soils to grow crops, with higher numbers indicating greater limitations to crop yields. We used a Spearman's Rank Correlation Test to test for correlations since residuals from regression analyses maintained a non-normal distribution, despite data transformations. Mean output values were calculated across all modeling units. All statistical analyses were conducted in R 3.2.1.

Results

Biomass and fuel production

In our simulations, switchgrass produced the most cellulosic biomass per ha, with an average yield of 4.4 Mg ha⁻¹ annually. The grass mixture produced the least and no-till corn was intermediate (Table 1). When both grain and cellulosic ethanol are considered, the

model simulations suggest no-till corn could produce approximately 2.5 and 4 times more ethanol per area than switchgrass and the grass mixture, respectively (Table 1). Yields for all feedstocks, including grain yields for no-till corn, were negatively correlated with slope and land-capability class ($P < 0.001$; P -values ranged from -0.490 for switchgrass yields and slope to -0.618 for no-till corn-grain yields and slope).

Soil and water quality impacts

No-till corn resulted in greater simulated soil and water quality impacts than the other two feedstocks. Soil erosion values were 4–5 times higher under no-till corn than for switchgrass and the grass mixture (Table 2). No-till corn resulted in a net loss of total soil C over time compared to the unharvested grass mixture; by contrast, switchgrass and the grass mixture increased soil C (Table 2; Fig. 2). Carbon lost in erosion and a reduction in C inputs in crop residues accounted predominantly for the decline in total soil C under no-till corn simulations. Respiration also declined under no-till corn, but this did not balance out the losses of C (Table 2). Larger C inputs from litter under the perennial feedstocks (mostly arising from belowground root litter) compared to the no-till corn was another factor explaining the divergent patterns in soil C dynamics (Table 2; Fig. 2). Nitrogen losses, particularly associated with sediment, were higher in the no-till corn vs. the other feedstocks (Table 2; Fig. 3).

When considered on a per unit ethanol basis (including both grain and cellulosic), no-till corn's soil and water quality impacts were closer to those of the other feedstocks given the greater amount of ethanol produced (Fig. 4). Both no-till corn and mixed grasses had similar

Table 1 Model outputs for simulations of feedstock production on Conservation Reserve Program land in Iowa. Shown are annual biomass, ethanol production per ha, and total cellulosic ethanol production, expressed in absolute values and as a percentage of the annual cellulosic ethanol target volume for the year 2022 in the Energy Independence and Security Act (EISA) of 2007. Results listed by feedstock type

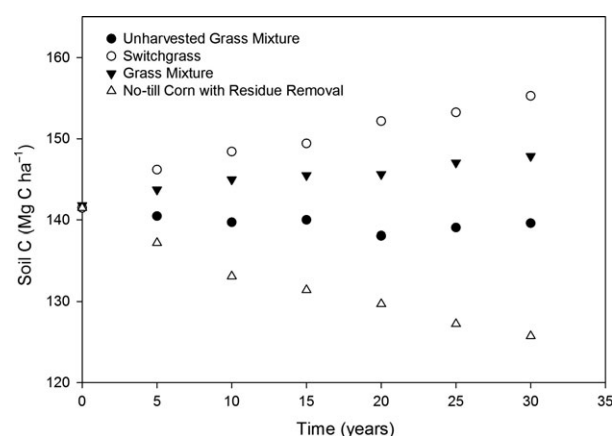
Model outputs	Switchgrass	Grass mixture	No-till corn with residue removal
Cellulosic feedstock yield, mean (5th and 95th percentile) (Mg ha ⁻¹ yr ⁻¹)	4.3 (2.0, 9.8)	2.6 (1.2, 6.9)	3.6 (3.0, 4.4)
Grain yield, mean (5th, 95th percentiles) (Mg ha ⁻¹ yr ⁻¹)	NA	NA	7.2 (5.9, 8.6)
Cellulosic ethanol, mean (L ha ⁻¹ yr ⁻¹)*	1653	970	1379
Grain ethanol, mean (L ha ⁻¹ yr ⁻¹)†	NA	NA	2903
Grain + cellulosic ethanol, mean (L ha ⁻¹ yr ⁻¹)	1653	970	4282
Total cellulosic ethanol produced over the 287 000 + ha simulated area (millions L yr ⁻¹)	474.9	278.7	396.4
Percent of cellulosic EISA target volume (ca. 60 billion L) in 2022	0.78	0.46	0.65

*Calculated using a conversion rate of 0.38 L of ethanol per kg biomass (Schmer *et al.*, 2008).

†Calculated using a conversion rate of 402.38 L of ethanol per Mg biomass (derived from Rendleman & Shapouri, 2007).

Table 2 Model outputs for simulations of feedstock production on Conservation Reserve Program land in Iowa. Shown are annual average soil erosion, and soil carbon (C) and nitrogen (N) stocks and fluxes by feedstocks and unharvested grass mixture

Model outputs	Unharvested grass mixture	Switchgrass	Grass mixture	No-till corn with residue removal
Soil erosion (Mg soil ha ⁻¹ yr ⁻¹)	0.2	3.1	3.6	14.1
Total soil C (Mg C ha ⁻¹)	139.9	155.6	147.9	126.0
C input from above- and belowground litter (Mg C ha ⁻¹ yr ⁻¹)	4.5	5.9	4.9	3.9
CO ₂ heterotrophic respiration (Mg C ha ⁻¹ yr ⁻¹)	4.5	5.3	4.6	4.0
C loss with sediment (kg C ha ⁻¹ yr ⁻¹)	4.4	91.2	77.0	317.8
Cumulative N loss (kg N ha ⁻¹ yr ⁻¹)	0.8	13.3	11.3	58.2
Sediment N loss (kg N ha ⁻¹ yr ⁻¹)	0.5	11.7	10.2	40.3
Surface N runoff (kg N ha ⁻¹ yr ⁻¹)	0.2	1.3	0.9	4.4
Nitrate leaching (kg N ha ⁻¹ yr ⁻¹)	0.1	0.2	0.1	13.5

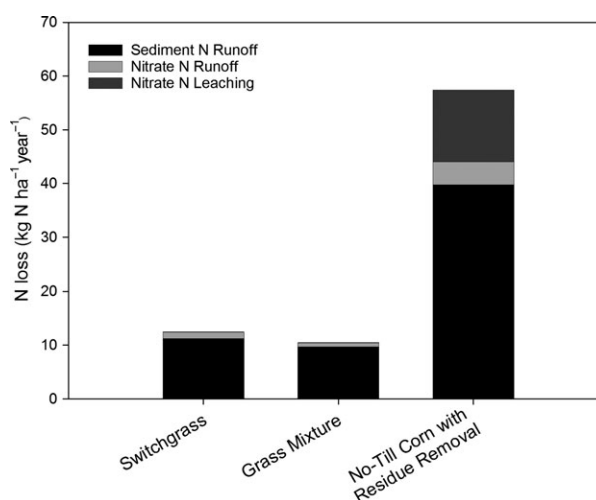
**Fig. 2** Soil carbon (C) stock (to a depth of ~1.5 m) by feedstock and unharvested grass mixture during the simulation period.

values for soil erosion and N loss on a per unit ethanol basis, although no-till corn still resulted in a loss of total soil C. Of the feedstocks, switchgrass produced the best environmental outcomes per unit ethanol.

Lastly, erosion relative to the unharvested grass mixture increased with slope and land-capability class under all feedstocks (Table 3; Fig. 5a). Nitrogen losses were also strongly correlated with slope and land-capability class for switchgrass and the grass mixture, but were only weakly associated with slope and land-capability class for no-till corn (Table 3, Fig. 5b). Changes in total soil C relative to the unharvested grass mixture were not strongly associated with slope or land-capability class for any of the feedstocks (Table 3).

Discussion

In this paper, we simulated the effects of producing cellulosic feedstocks for over 200 000 individual mod-

**Fig. 3** Annual soil nitrogen (N) loss by feedstock type, expressed relative to the unharvested grass mixture.

eling units, making up ca. 290 000 ha of CRP – either currently in the program or recently exited. These simulations suggest that CRP land can be used to produce cellulosic biofuel feedstocks, but that careful consideration of environmental vs. energy trade-offs are warranted.

Biomass and ethanol yields

The yields simulated here by EPIC are generally within the range of published field trials in the Midwestern US. Tilman *et al.* (2006) reported annual yields of prairie grass of approximately 3.7 Mg ha⁻¹ in study plots on degraded soils in Minnesota. Average switchgrass annual yields of 5.2–11.1 Mg ha⁻¹ have been observed in established fields in the Great Plains (Schmer *et al.*, 2008), and in a recent study, Bonin & Lal (2014) found

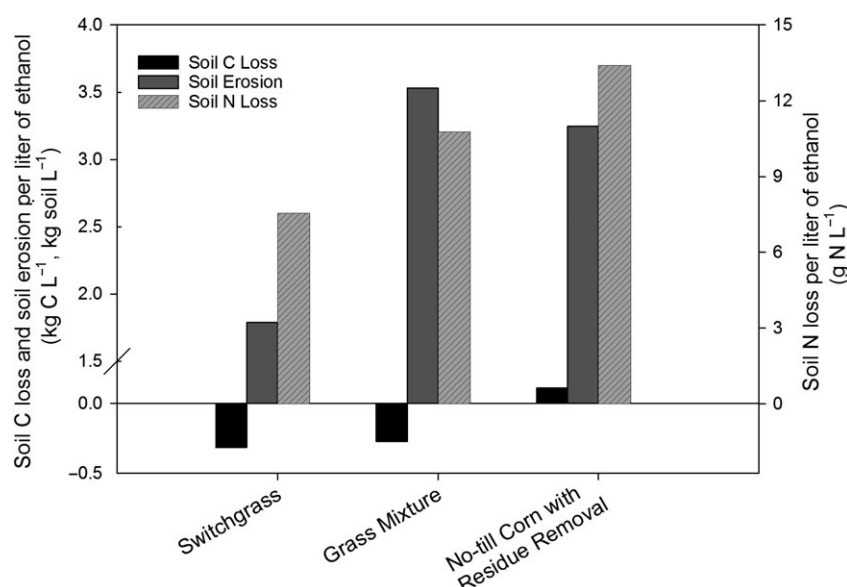


Fig. 4 Soil carbon (C) and nitrogen (N) loss and erosion by feedstock type relative to the unharvested grass mixture, expressed on a per-unit ethanol basis. Note: negative soil C loss values denote a net increase in soil carbon.

Table 3 Spearman's Rank Correlation Test *P*-values for correlation between soil and water quality impacts of each feedstock relative to the unharvested grass mixture, and slope and land-capability class (note: *P*-values in this test range from 0 to 1, with stronger relationships indicated by numbers closer to 1). All correlations were significantly positive ($P \leq 0.001$)

	Soil erosion	Cumulative N loss	Total soil C
Land-capability class			
Switchgrass	0.774	0.702	0.104
Grass mixture	0.748	0.736	0.206
No-till corn with residue removal	0.765	0.076	0.294
Slope			
Switchgrass	0.913	0.832	0.115
Grass mixture	0.892	0.895	0.236
No-till corn with residue removal	0.893	0.155	0.322

average corn stover yields of 4.1 and 13.1 Mg ha⁻¹ at two sites in Ohio. Nationwide, 2015 corn-grain yields were estimated by the USDA to average approximately 8.9 Mg ha⁻¹ after accounting for moisture content (15.5%) (USDA-NASS, 2015). In all these cases, the averages reported are well within our simulated range (Table 1), except for the high corn stover yield in Ohio (Bonin & Lal, 2014) and the nationwide corn-grain yield average (USDA-NASS, 2015). Conservation Reserve Program land is typically less productive than prime farm land, likely explaining the lower simulated corn yields

compared to a highly productive site and the nationwide average.

It is constructive to consider that at these simulated yields, there is not enough CRP land nationwide to meet the cellulosic goals of EISA. Volumes of cellulosic biofuels have been lagging behind EISA targets – ca. 125 million L of cellulosic biofuel were produced in 2014, far smaller than the EISA set-goals of 6.6 and 60 billion L annually for 2014 and 2022, respectively (US EPA 2010, 2015). According to the model, switchgrass had the highest yield of cellulosic ethanol per hectare (1653 L ha⁻¹) of all the feedstocks. If that yield is extrapolated, by multiplying it by all the area currently under CRP nationally (9.5 million ha; USDA-FSA, 2015), the volume of cellulosic ethanol produced (ca. 15.8 billion L) would still only yield about 25% of the 60 billion L cellulosic ethanol volume EISA requires annually. Expressed another way, it would require more than 3.5 times the current enrollment of CRP nationally to meet the EISA target. Further, CRP land includes tree plantings, windbreaks, wetland restorations, and other land-covers less suitable for farming than the CRP grasslands studied here. Thus, these results suggest CRP-produced cellulosic ethanol could not by itself meet targets set by Congress; rather, it would need to be a contributing piece, amongst many other land-use types and feedstocks.

Environmental impacts

Our results indicate that if only total ethanol production is considered, corn would be the preferred feedstock of the three simulated due to its high starch and cellulosic

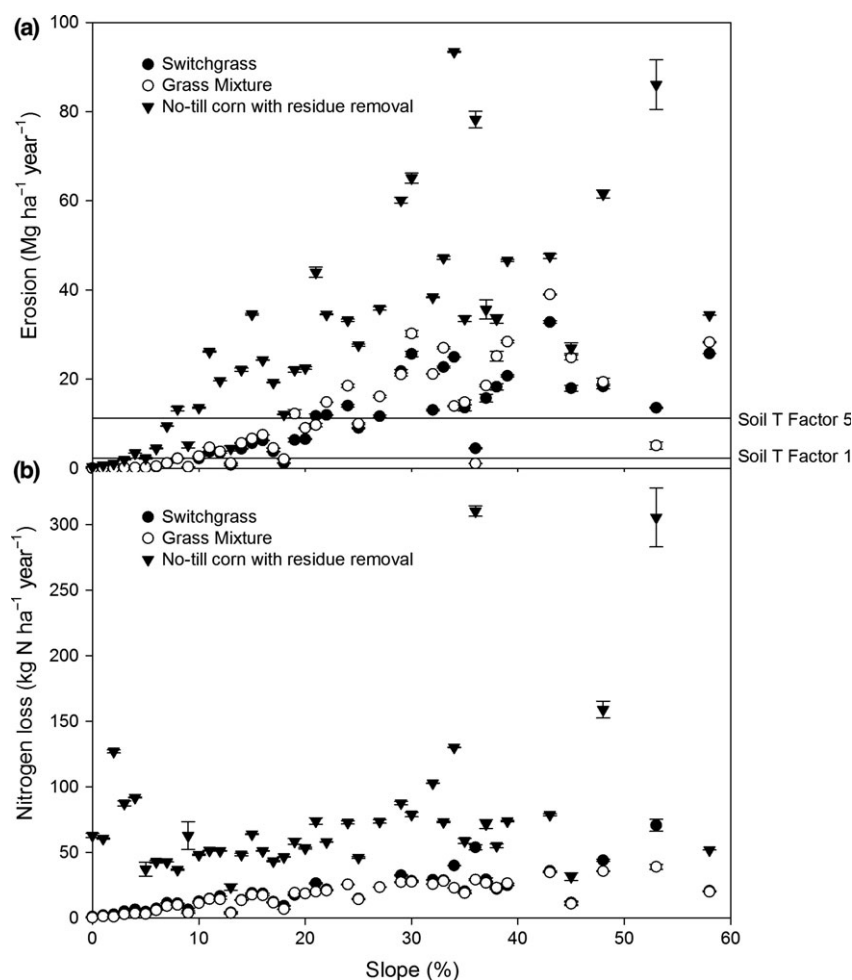


Fig. 5 Soil erosion (a) and nitrogen loss (b) by slope for the three feedstock types relative to the unharvested grass mixture. Symbols represent mean values for all modeling units with a given slope; error bars equal ± 1 SE. Horizontal lines depict soil loss tolerances for deep soils (Soil T Factor 5) and for shallow or otherwise fragile soils (Soil T Factor 1).

output for ethanol production. However, if judged on environmental effects, our findings suggest no-till corn with residue removal would cause much greater negative environmental effects than perennial grasses. When expressed on a per-unit ethanol basis, the erosion and N loss of no-till corn are similar to the grass mixture (though not for carbon loss), but even then, switchgrass would still yield better environmental outcomes (Fig. 4).

These findings are consistent with other studies. Gelfand *et al.* (2011) found CRP grassland conversion to no-till continuous corn (without residue removal) could result in a total carbon debt of 68 Mg CO₂ equivalents ha⁻¹, requiring 40 years to repay with the C savings from the displacement of gasoline. In a meta-analysis of literature values, Anderson-Teixeira *et al.* (2009) concluded corn residue harvesting resulted in large average soil organic C losses even in no-till systems, predicting losses of 3–8 Mg ha⁻¹ over 10 years' time under 25%

and 100% residue removal. Here, soil C losses averaged 6.6 Mg ha⁻¹ over the first 10 years of the simulations, and continued over the entire 30 year period (Fig. 2). Conversely, growing switchgrass and mixed prairie grasses resulted in a simulated increase in soil C, 8.7 and 5.3 Mg ha⁻¹ over the first 10 years, respectively, and 15.7 and 8.3 Mg ha⁻¹ over the entire 30 years, respectively. The effects of N amendments and higher residue inputs, particularly under switchgrass, likely explain this increase in soil C (Liebig *et al.*, 2008). This also suggests these CRP soils may not have reached C equilibrium even after years of perennial cover, a finding supported by field-based evidence (Gebhart *et al.*, 1994; Gelfand *et al.*, 2011; O'Connell *et al.*, 2016)).

No-till corn also resulted in much higher soil erosion and N loss relative to the perennial grasses (Table 1). Simulated erosion for no-till corn averaged 14.1 Mg ha⁻¹, above the average water erosion rate of

12.2 Mg ha⁻¹ on cultivated land in Iowa (USDA-NRCS, 2013); the soil loss tolerance for deep soils (11.2 Mg ha⁻¹); and much higher than the soil loss tolerance for most shallow or otherwise fragile soils (2.2 Mg ha⁻¹) (USDA-NRCS, 2015a). These soil loss tolerance levels are the maximum rates of annual soil erosion permitting sustainable crop productivity (USDA-NRCS, 2015a). Strikingly, the perennial grasses minimized, but did not eliminate, erosion according to the model. EPIC uses a modified version of the universal soil loss equation (USLE; see Data S1) to estimate erosion. Harvesting biomass increases erosion by reducing surface cover, which affects the cover-management factor in the USLE. In our simulations, switchgrass and the grass mixture had erosion rates (3.1 and 3.6 Mg ha⁻¹, respectively) marginally higher than the soil loss tolerance for the most shallow or otherwise fragile soils, and much lower than the tolerance classes for other soils. The erosion rates simulated were also similar to those observed on noncultivated or pastureland in Iowa (USDA-NRCS, 2013), and were almost entirely driven by erosion on steep slopes (above 20%; further discussed below). Field studies of erosion rates under harvested perennial grass systems are generally lacking, limiting direct comparisons (Blanco-Canqui, 2010). Most of the research to date has focused on the erosion reduction benefits of planting perennial grasses in buffer strips, which have been shown to substantially reduce, but not always eliminate erosion (Blanco-Canqui, 2010). Field trials incorporating the harvesting of perennial grasses for biomass on steeper, erosion-prone slopes are needed to more fully evaluate this finding.

We found that all of these biofuel types are likely to contribute to N loadings, especially no-till corn. The perennial grasses greatly reduced N loss relative to the no-till corn (Fig. 3), but did increase N loss relative to the unharvested grass mixture. The greatest loss of N was associated with sediment erosion under the no-till corn treatment. The N losses under the no-till corn are similar in magnitude to those found in field observations. Zhu & Fox (2003) for instance, observed annual nitrate (NO₃⁻) leaching averages of 20 and 41 kg N ha⁻¹ in a no-till corn system (without residue removal) receiving 100 kg N ha⁻¹, while we simulated an annual loss of 13.5 kg N ha⁻¹ via NO₃⁻ leaching and a total N loss of 58.2 kg N ha⁻¹ under a similar fertilization rate. EPIC is an edge-of-field model and so N lost may not necessarily enter waterways, but it certainly suggests these biofuel types could contribute to N loadings, especially if no-till corn were grown on CRP land. If widespread across the Mississippi River Basin, increased biofuel production on CRP land would be in conflict with the goal of reducing nutrient loads and shrinking

the hypoxic zone in the Gulf of Mexico (Gulf Coast Ecosystem Restoration Task Force 2011).

Our simulations predict most environmental impacts would arise from producing these feedstocks on steeper sloped CRP land. Under no-till corn, most simulated erosion above soil loss tolerance levels occurred on lands with a slope of 10% or greater (Fig. 5a). For the perennial grasses, this occurred on lands with a slope of 20% or more (Fig. 5a). Likewise, N loss was significantly correlated with slope, with much of these losses associated with erosion (Table 3; Fig. 5b). We also found a decline in yields for all feedstocks with slope. This occurred despite higher sloped soils being a small fraction of the area modeled. More than half of the area modeled (ca. 148 000 ha) contained soils with slopes of less than 10%, and over 95% of the area contained soils with slopes of less than 20% (274 000 ha). These findings are echoed by other studies. Secchi *et al.* (2009) used EPIC to simulate the effects of converting CRP to corn-ethanol production and found greater erosion and N loss rates at higher slopes under continuous corn production. Likewise, in field experiments, Blanco-Canqui & Lal (2007, 2008) found corn stover removal negatively impacted soil nutrients, C, and grain and stover yields, particularly on steeper soils.

It may be that a lower corn stover removal rate than the one simulated here (50%) would have reduced some of the environmental effects on the steep sloped soils. Graham *et al.* (2007) suggested a national stover removal rate of 30% to keep erosion below soil tolerance loss levels. Blanco-Canqui & Lal (2007, 2008) concluded that a removal rate of 25% or less may be sustainable, a finding based on soils with slopes of ≤10%, much less than some of the slopes simulated here. At these low removal rates, however, it might not be economically profitable to remove stover. Given the environmental concerns, reductions in yield, and the difficulties farming these steep soils, it may be that producers avoid these soils altogether. Overall, our results suggest it makes best economic and environmental sense to preferentially use flatter, deeper CRP soils and not steeper sloped CRP land.

Notably, areas in CRP have been declining nationally, with much of this land going back to agriculture (USDA-NRCS, 2015b). Broader than CRP, recent studies have shown large-scale conversions of grasslands to agriculture in the US, predominantly to corn and soybeans (Wright & Wimberly, 2013; Lark *et al.*, 2015). Here, we compared our results to a baseline of an unharvested grass mixture, and we did not explicitly compare to row-crop agriculture. Nevertheless, growing perennial grasses for feedstocks is likely to provide better environmental outcomes than annual row crops (Ranney & Mann, 1994). Thus, against this backdrop, a cellulosic perennial grass industry might afford a means

to keep CRP land under perennial cover, and provide more environmental benefits than the current status quo of converting it back to intensive row-crop agriculture. By contrast, it is possible that a corn stover industry could further incentive an expansion of corn and corn stover removal onto marginal lands, including CRP land. Our study suggests the environmental outcome of this would be worse than growing perennial grasses for biofuel feedstocks.

When evaluating the results of this study, it is important to note what was not considered in our modeling approach. This research study focused on select environmental end-points, namely soil C, N, and erosion. Conservation Reserve Program land, and other set-aside areas, however, provide environmental benefits not considered here – for example, wildlife habitat. Moreover, we did not consider any potential effects from the production of feedstocks on the economic benefits of these lands, such as hunting and recreation. We also focused on Iowa and three particular types of feedstocks. Other feedstocks in other areas may present alternative benefits or impacts. Finally, we did not include social drivers in our analysis. Recent research, for instance, suggests that landowner preferences may pose a barrier to growing cellulosic biomass on marginal lands (Skevas *et al.*, 2016).

Conclusions

In this study, we employed a CRP field-level database and modeling framework to simulate the effects of producing biofuel feedstocks on over 200 000 individual modeling units, representing 290 000 ha of former or current CRP grasslands. We conclude that CRP land can be used to produce substantial volumes of grain and cellulosic ethanol. Ignoring environmental effects, corn would be the preferred feedstock due to its high grain and cellulosic output for ethanol production, producing approximately 2.6–4.4 times more ethanol per area compared to switchgrass and the grass mixture. However, when environmental considerations are included, the balance changes. No-till corn led to 3.9–4.5 times more erosion, 4.4–5.2 times more cumulative N losses, and a 10% reduction in total soil carbon as opposed to a 6–11% increase. Switchgrass resulted in the best environmental outcomes in absolute terms and on a per unit ethanol basis. Our simulations further suggest planting no-till corn with residue removal should only be done on the lower slope soils (with slopes less than 10%) in order to avoid some of the most negative effects. Relevant to all feedstock types simulated here, we conclude CRP land can only meet a small fraction of the cellulosic volume goal set by the 2007 EISA if these results from Iowa hold for the nation. Thus, growing cellulosic biomass on CRP land

would likely need to be a smaller part of a larger portfolio of renewable energy, rather than viewed as a ‘silver bullet’. Overall, this analysis provides additional information to policy makers on the potential outcomes and effects of producing feedstocks on current or former conservation areas.

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Supporting Information

Additional Supporting Information may be found online in the supporting information tab for this article:

Data S1. EPIC model description.

Data S2. EPIC simulations in a spatially explicit integrated modeling framework.

Figure S1. Depiction of the spatially explicit integrated modeling framework used to model homogenous spatial modeling units (HSMU) (Redrawn from Zhang *et al.*, 2010).